GREEN TO GREENER--IS BIODIESEL A FEASIBLE ALTERNATIVE FUEL FOR U.S. ARMY TACTICAL VEHICLES?

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This thesis examines the feasibility of using biodiesel-blended fuel to operate U.S. Army tactical vehicles within the continental United States (CONUS). The mixed methodology included quantitative and qualitative data, synthesizing two primary source studies focused on multiple factors such as diesel engine performance, vehicle maintenance, fuel storage, and diesel-vehicle fleet operator satisfaction with biodiesel-blended fuel. Additionally, this study performed quantity analysis to compare U.S. Army CONUS fuel requirements and domestic biodiesel production figures through 2007. Qualitative measures indicate a high degree of satisfaction among vehicle fleet operators who use biodiesel-blended fuel. Within the limited scope of the primary source studies, the quantitative assessment revealed that biodiesel-blended fuels cause no greater incidence of engine or fuel system malfunctions. Further, the fuel quantity analysis indicates that current biodiesel production in the U.S. is sufficient to displace an appreciable percentage of the U.S. Army's CONUS fuel requirement for tactical vehicles. Because no vehicle modifications are required to operate on biodiesel-blended fuel and vehicles can safely resume using 100 percent petroleum diesel fuel, the U.S. Army has a great potential to reduce fossil fuel consumption in CONUS training and operations, while not impacting the single-fuel (JP-8) distribution for world-wide operations. Additional biodiesel experimentation is warranted to obtain more precise data regarding performance factors and maintenance requirements of tactical vehicles while using biodiesel-blended fuel.

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ABSTRACT

GREEN TO GREENER--IS BIODIESEL A FEASIBLE ALTERNATIVE FUEL FOR U.S. ARMY TACTICAL VEHICLES? by MAJ Tracy Lee Barker, 87 pages.

This thesis examines the feasibility of using biodiesel-blended fuel to operate U.S. Army tactical vehicles within the continental United States (CONUS). The mixed methodology included quantitative and qualitative data, synthesizing two primary source studies focused on multiple factors such as diesel engine performance, vehicle maintenance, fuel storage, and diesel-vehicle fleet operator satisfaction with biodiesel-blended fuel. Additionally, this study performed quantity analysis to compare U.S. Army CONUS fuel requirements and domestic biodiesel production figures through 2007. Qualitative measures indicate a high degree of satisfaction among vehicle fleet operators who use biodiesel-blended fuel. Within the limited scope of the primary source studies, the quantitative assessment revealed that biodiesel-blended fuels cause no greater incidence of engine or fuel system malfunctions. Further, the fuel quantity analysis indicates that current biodiesel production in the U.S. is sufficient to displace an appreciable percentage of the U.S. Army's CONUS fuel requirement for tactical vehicles. Because no vehicle modifications are required to operate on biodiesel-blended fuel and vehicles can safely resume using 100 percent petroleum diesel fuel, the U.S. Army has a great potential to reduce fossil fuel consumption in CONUS training and operations, while not impacting the single-fuel (JP-8) distribution for world-wide operations. Additional biodiesel experimentation is warranted to obtain more precise data regarding performance factors and maintenance requirements of tactical vehicles.

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ACRONYMS

ACOM	U.S. Army Command
ACP	Army Campaign Plan
AEF	Africa Eco Foundation
AMC	U.S. Army Materiel Command
ASTM	American Society for Testing and Materials International
BCT	Brigade Combat Team
BLT	Bundesanstalt fur Landtechnik
BOD	Biochemical Oxygen Demand
Btu	British Thermal Unit
CFPP	Cold Filter Plug Point
CO	carbon monoxide
CONUS	Continental United States
CSIR	Council for Scientific and Industrial Research
CUCV	Commercial Utility Cargo Vehicle
DESC	Defense Energy Support Center
DOE	United States Department of Energy
DOD	United States Department of Defense
EIA	Energy Information Administration
EPA	United States Environmental Protection Agency
EPACT	Energy Policy Act
EU	European Union
EU CEN	European Union Committee on Standardization

GSA	General Services Administration
HBCT	Heavy Brigade Combat Team
HEMMT	Heavy Expanded Mobility Tactical Truck
HMMWV	High Mobility Multi-Purpose Wheeled Vehicle
IBCT	Infantry Brigade Combat Team
IMCOM	U.S. Army Installation Management Command
NBB	National Biodiesel Board
NREL	National Renewable Energy Laboratory
NOx	nitrogen oxide
OEM	Original Equipment Manufacturer
OPEC	Organization of Petroleum Exporting Countries
PM	particulate matter
SBCT	Stryker Brigade Combat Team
TASS	The Army School System
TECOM	U.S. Army Test and Evaluation Command
THC	total hydrocarbons
TRADOC	U.S. Army Training and Doctrine Command
ULSD	Ultra Low Sulfur Diesel
U.S.	United States
USDA	United States Department of Agriculture
WFP	United Nations World Food Program
YPG	U.S. Army Yuma Proving Grounds

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CHAPTER 1

INTRODUCTION

Purpose

This chapter provides a background summary on the ascent of petroleum fuel in the twentieth century and fuel's linkage to social, political, and economic issues. These issues are presented as U.S. national security concerns, introducing the thesis question as a possible means to improve the U.S. national security posture.

Background

In the early decades of the twentieth century, the United States had virtually no competitors for petroleum. America's newfound prominence upon the world stage following World War I was characterized by increased industrialization, rapid economic growth, and a seemingly infinite supply of resources and raw materials to feed that growth. Crude oil was among those resources that seemed endless. The supply of oil far exceeded the nascent demand (Heinberg 2003, 55). For example, in 1920, the *New York Times* reported that refined petroleum product exports increased significantly despite increased domestic consumption (*New York Times* 1921). Oil drawn from the earth domestically and in many other parts of the world soon became the economical fuel of choice for heating, manufacturing, and transportation.

Too soon, however, competition for energy resources stirred conflict. Scarcity of energy resources drove Japan and Germany toward conquest, initiating the century's second Great War. The United States embarked on a total war effort by fully mobilizing people and industry. Rationing commodities at home enabled more resources in the fight abroad, and American citizens endured rationing as a patriotic duty. Following the war, global sources of oil were once again free-flowing, stimulating the greatest economic expansion in American history through the 1950s and 1960s (Heinberg 2003, 40).

America's economy, a significant United States national security interest, remains inexorably tied to oil. Oil is the common element to almost all American products and services, from fuels for transport by road, rail, sea, or air, to manufacturing and pharmaceuticals. Oil remains the prime commodity of the world's economy because there is currently no alternative.

The Organization of Petroleum Exporting Countries (OPEC) formed in 1960 to collectively negotiate the interests of member countries. Charter member nations included Iran, Iraq, Kuwait, Saudi Arabia, and Venezuela. Eight additional countries joined OPEC during the 1960s and early 1970s. OPEC sought to control crude oil production in order to maintain favorable market prices. Prior to OPEC's inception, multinational oil companies set market prices for oil and contract prices for oil exploration. OPEC's emergence as a powerful cartel signaled the transition in the balance of power between oil producing countries, the major oil companies, and western consumers. This new order soon demonstrated both political and economic consequences.

In the early 1970s, western nations, particularly the United States, were abruptly made aware of their vulnerability to foreign-supplied oil and the related consequences. OPEC countries agreed to an embargo of oil exports to the west in response to Anglo-American support of the Israelis in the 1973 Yom Kippur War. The impact of the embargo was immediate; American and European fuel prices quadrupled within weeks.

A $3.00 barrel of oil before the embargo rose to $11.65 by January, 1974 (University of California at San Diego 2008). Long lines at fuel stations compounded consumers' frustrations, and the rapid price increases ultimately affected nearly all sectors of the American economy. Double-digit inflation, interest rates, and unemployment rates reflected the broad effects that persisted for several years. The Consumer Price Index, an indicator of the average purchase price for household goods and services, rose approximately ten percent annually in the late 1970s (Heinburg 2003, 73). Interest rates on home mortgages remained above ten percent from 1979 to 1991, peaking at 16 percent in 1981 (United States Federal Reserve 2008). Similar effects of economic recession occurred in Europe and Asia, where Japan's economy shrank in terms of gross national product for the first time since World War II. The world recognized oil as not only a critical commodity but also as a potent economic weapon (University of California at San Diego 2008).

In 1977, President Jimmy Carter sought to reform America's energy management. Responding to these events, the president and Congress created the Department of Energy (DOE) with passage of the Department of Energy Organization Act. Prior to this legislation, numerous federal agencies managed multiple sectors of U.S. energy policy. The DOE united policy, planning, and research and the development efforts of the Federal Energy Administration, the Energy Research and Development Administration, the Federal Power Commission, and parts and programs of several other agencies (U.S. Department of Energy 2008).

Dismal economic conditions inhibited Carter's re-election at the conclusion of his term, and in 1980, Ronald Reagan won the presidential election. The Reagan administration held a free-market perspective about energy management, believing that the equilibrium between supply and demand would maintain stability even through short-duration crises (Donovan 1982). President Reagan signed legislation that eliminated price controls and other artificial mechanisms, such as import tariffs and product allocation programs, imposed by the Carter administration. In 1983, crude oil futures trading began on international exchange markets. This development represented a second shift in as many decades for control of crude oil prices. The consumer market, not major oil companies or the OPEC cartel, dictated price (Sjuggerud 2004). Despite adding the potential hazard of speculation, especially in supply crises, Reagan's policies (combined with increased domestic production by tapping Alaska's North Slope oilfields) achieved supply and price stability.

The Issues

The oil supply of the last thirty years has been relatively stable. This stability is both good and bad. It is good in that the stability enabled economic growth and improved American standards of living. Conversely, it is bad because the American automotive industry has had little incentive to seek alternative fuel sources and technologies, at least not on the scale to introduce a clear alternative to petroleum. Stable supplies and prices also stimulated global economic growth, thus increasing the demand for oil. Increased global demand creates other challenges, such as resource depletion and climatic change as a result of pollution from burning fossil fuels.

In the United States, oil production in the "lower 48 states" peaked in 1970 at 9.2 million barrels per day and has been declining steadily since (Sandalow 2008, 42). Similar peak events are occurring elsewhere among oil producing countries in Europe, South and Central America. Exceptions include Africa, the Middle East, and Far East, where production has increased in response to global demand and declining production elsewhere. Figure 1 shows the estimated global oil production by geographic region. The eventual peak in global oil production, or "peak oil," is a concept introduced by Marion King Hubbert to his contemporaries at an annual meeting of the American Petroleum Institute (Clark 1983).

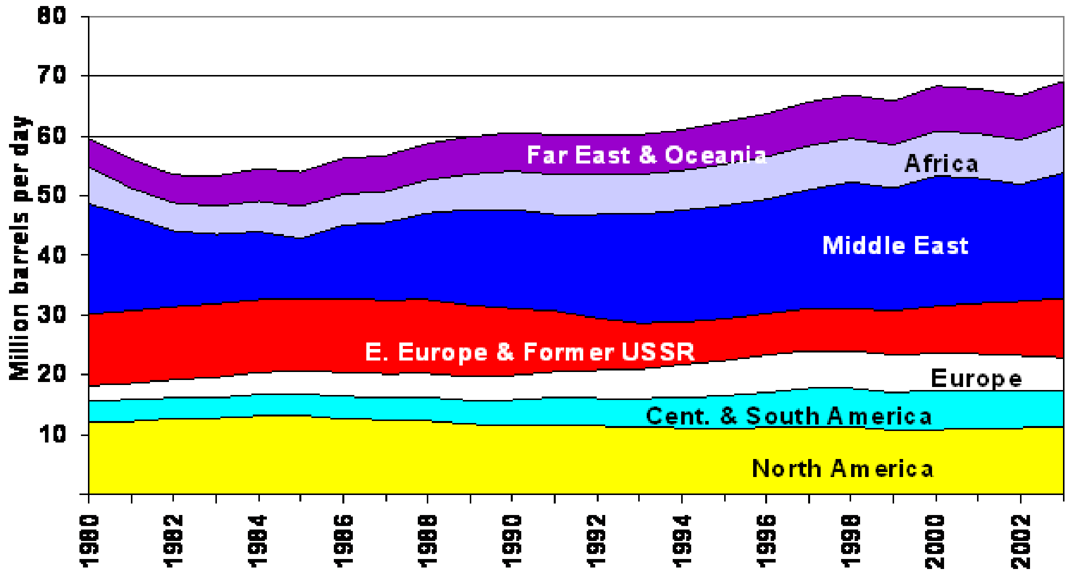

Figure 1. Global Oil Production by Region, 1980-2003
Source: Energy Information Administration, Website, http://www.eia.doe.gov (accessed 7 February 2009).

Hubbert is perhaps the best known American geophysicists in the twentieth century. In 1949, he declared that "the fossil-fuel era would prove to be very brief" (Heinberg 2003, 87). Later, in 1956, Hubbert predicted that U.S. oil production would peak between 1966 and 1972. Only in hindsight was Hubbert's narrow (specific to the contiguous United States) prediction determined to be correct, as hindsight will also be the case for the future global peak in production. The world will not recognize production has peaked until after it has occurred (Sandalow 2008, 42). Using a similar calculation method to the 1956 estimate, Hubbert approximated a global peak oil date between 1990 and 2000 (Heinberg 2003, 90). Subsequent researchers and petroleum geologists, within private sector industry and among governmental agencies, continue to evaluate data to estimate the date of global peak oil production. Though estimated dates differ, there is consensus on one point--peak oil is a question of "when," not a question of "if."

Beyond the impending depletion of oil and its broad economic impact, the world is also imperiled by the negative environmental and health implications of consuming fossil fuels. Greenhouse gas emissions, attributed by many to cause global warming, emerged at the close of the twentieth century as a significant health threat. Forty percent of worldwide carbon dioxide emissions are the result of burning petroleum (Sandalow 2008, 30).

The Thesis Problem

The Department of Defense is the largest single consumer of oil in the United States (Bender 2007). Within the United States Army, oil is consumed primarily in the form of aviation fuel and ground vehicle diesel fuel, known as JP-8. The U.S. Army consumes millions of gallons of JP-8 annually in training and daily operations, not to mention the additional estimated 2 million gallons consumed daily in combat-zone operations in Afghanistan and Iraq (Flaherty 2008).

The Army expects currently fielded wheeled and tracked ground vehicles and power-generation sets powered by diesel, turbo-diesel, or diesel-turbine engines to remain in the Army's inventory through the year 2050. Vehicles being fielded now and those proposed to be fielded in the next ten to fifteen years also rely on diesel engines (Erwin 2009).

America's national security vulnerability boils down to these facts: no substitute for oil exists, demand for oil is increasing, supplies are being exhausted, and America's economic and physical health is at risk.

Several developments, while not new, have emerged in the past decades that hold potential specifically as solutions to America's oil dependency. These prospective solutions are renewable and sustainable, meaning they are organically-based and can be literally grown year after year. They are produced domestically, which eliminates any potential of artificial manipulation by a foreign monopoly or cartel. Finally, they are environmentally cleaner than fossil fuels. These prospective solutions are called biofuels, and include ethanol, methanol, and biodiesel. This thesis, therefore, seeks to answer the primary question of whether it is feasible to fuel U.S. Army tactical vehicles with biodiesel. In order to answer this question, several secondary questions must be addressed. They are:

1. Does biodiesel-blended fuel cause any greater incidence of engine malfunction than standard diesel fuel (JP-8) in U.S. Army tactical vehicles?

2. Does biodiesel-blended fuel require modification to the U.S. Army's existing fuel storage and distribution infrastructure?

3. What quantity of biodiesel is produced within the United States that could be used to displace the U.S. Army's (CONUS) annual fuel (JP-8) requirement?

Summary

Chapter 1 describes the ascent of petroleum fuels in the twentieth century. This chapter further described the social, political, and economic issues related to petroleum fuel in terms of U.S. national security vulnerabilities. Finally, chapter 1 introduces the thesis question, asking whether biodiesel is a feasible alternative fuel for U.S. Army ground tactical vehicles.

CHAPTER 2

LITERATURE REVIEW

> The use of vegetable oils for engine fuels may seem insignificant today, but such oils may become, in the course of time, as important as petroleum and the coal-tar products of the present time.
>
> — Rudolf Diesel, 1912

Introduction

This chapter presents the review of current literature concerning biodiesel fuel. It provides a chronological history of recent biodiesel research and development, and describes the fuel's characteristics, including advantages and disadvantages. This chapter provides data regarding commercial biodiesel production and addresses numerous considerations regarding biodiesel use. Finally, this chapter presents two case studies, forming a portion of the data for analysis in support of the thesis question. Subsequent chapters describe the methodology employed in this study, the findings and analysis, and the author's conclusions and recommendations.

Background

Early Biodiesel Research

The modern era of alternative fuel investigation followed the oil crisis of 1973. Oil prices and subsequent conditions of economic inflation described as painful in the U.S. were paralyzing in other countries. Western Europe, with the exception of the United Kingdom, possessed no appreciable oil reserves. These countries quickly revived their interest in alternative fuels. South American countries such as Brazil and Argentina were likewise attracted to petroleum alternatives, and they chose primarily to pursue ethanol as a gasoline substitute.

Austria's government initiated a small-scale biofuel experiment in the mid-1970s. The experiment focused on farm diesel tractors, and was led by the Federal Institute for Agricultural Engineering (Bundesanstalt fur Landtechnik, or BLT). A prominent European engine manufacturer, AVL-List, partnered with BLT for the experiment. They conducted tests by mixing linseed oil with petroleum diesel in various proportions. Tractors operated normally for a specific duration, and then the engines were disassembled for professional technical inspection to determine the effects. The results indicated that use of oil-diesel blends would damage diesel engines when used over extended periods.

At the University of Idaho in 1979, researchers in the College of Agriculture had a similar idea. The college experimented with petroleum diesel and sunflower oil blends. Successful experiments evolved to operating diesel tractors on pure sunflower oil and subsequently safflower oil, but their results were similar to the findings of BLT in Austria; "As most of the early biodiesel researchers quickly discovered, using straight plant oils as a fuel substitute in diesel engines was not especially good for the engines" (Pahl 2007, 42).

BLT engineers continued to research literature and reports regarding alternative fuel technology from around the world. They concluded that either the vegetable oils must be adapted to the diesel engine, or the diesel engines must be adapted to the vegetable oils. The latter was thought to be impractical, since the number of diesel engines worldwide, employed in various forms, was enormous. The prospect of retrofitting millions of existent engines and modifying the manufacture of new engines was not realistic. A process to chemically alter the vegetable oils would be necessary.

The persistent research of BLT engineers paid off in 1981, when they discovered similar research was being conducted in France and South Africa and elsewhere at home in Austria. The French and South African researchers had experimented using a standard chemistry process called transesterification, to modify vegetable oils. Simultaneously, chemists at the University of Graz, Austria, were also researching the potential of modified vegetable oils as fuel. The subsequent cooperative effort between BLT engineers and the Graz chemists was the first inexpensive process to convert vegetable oils to diesel fuel (Pahl 2007, 32). They published their process and findings from subsequent bench tests and field trials in 1982.

Recent biodiesel research /development

The transesterification process opened biodiesel development, research, and use to the global community. Knowledge and information spread quickly through energy and agriculture research literature. By the early 1990s, plant oils were being converted to fuel on a larger yet still modest scale for niche applications such as university, municipal, and state utility vehicle fleets. These applications served to broaden awareness among the public and private sectors worldwide.

Internationally, biodiesel has surged to the forefront among nations seeking to reduce external energy dependence. Europe leads the world in biodiesel research, development, and implementation. Silberberg Agricultural College in Styria, Austria started the first biodiesel production facility in 1985, and similar programs gradually spread across the continent. As of 2007, there are hundreds of commercial biodiesel production plants in Europe. European producers, like many American counterparts, focus on source flexibility and production efficiency.

Most European research involves rapeseed oil, which is the most commonly produced plant oil on the continent, and more recently on used frying oil recovered from food production sources. Because vegetable oil is subject to commodity market fluctuation, these producers invest in the capability to produce biodiesel from multiple feed-stocks or sources. The result is price stability for the consumer. Another producer focus is efficiency. Early biodiesel processing yielded in the 85 percent to 95 percent range, based on volume of the source oils. Today, improved processing systems achieve yields of 100 percent in modern facilities (Pahl 2007, 87).

Biodiesel research and production is also expanding through the African, Asian, and South American continents. Much of that research is focused on native or regionally grown feed-stocks particular to each country. South Africa, for example, was the subject of a study by the United Nations which identified an enormous potential for biodiesel production (Pahl 2007, 124). A similar report in 2008 by South Africa's Council for Scientific and Industrial Research (CSIR) stated that increased production of biodiesel may decrease the country's dependence upon imported petroleum and strengthen agriculture while providing new jobs in rural areas (Budoo, S.R. 2008).

These two objectives are pursued by many countries with nascent biodiesel industries. Within Africa, there are numerous countries participating in a project sponsored by the Africa Eco Foundation (AEF). AEF is a non-government organization based in South Africa, which has implemented a model suited to the relatively poor, under-developed region. Their strategy involves land reclamation through the planting and cultivation of native oil bearing plants. Ownership is focused at the community level, and it relies more on physical labor and less on the technology found in modern, industrialized countries. This African project is proving that biodiesel production technology is highly adaptable, not constrained to wealthy nations, and is viable on large or small scales of operation (Agence France-Presse 2002).

The background section of this chapter describes the evolution of biodiesel development and sets the stage to introduce several of the key sources for this literature review. Prominent sources include governmental agencies such as the Environmental Protection Agency, the Department of Energy, and subordinate agencies, such as the National Renewable Energy Laboratory, and Energy Information Administration. Additional sources include American colleges of agriculture and engineering, such as the University of Idaho and North Dakota State University. These authoritative sources are cited due to their documented scholarship and contributions in the field of biodiesel development over the past two decades.

Greg Pahl, author of *Biodiesel: Growing a New Energy Economy*, is widely recognized as the preeminent author with respect to biodiesel. His book is a comprehensive work addressing biodiesel development, past and present biodiesel initiatives, and future possibilities tempered by the realities of the real-world social, economic, and political environment.

Biodiesel Production in the U.S.

The U.S. is second to Europe in biodiesel production. U.S. production capacity is growing rapidly, according to data presented by the United States Department of Energy's Energy Information Administration (EIA). The EIA estimates 2007 production at 491 million gallons (EIA 2009). Comparing production from preceding years gives some scale to the rate of biodiesel growth in the United States. For example, the EIA report cited above shows production at 250 million gallons in 2006, and 91 million gallons in 2005 (EIA 2009).

The National Biodiesel Board indicates that 171 commercial production facilities operate within the U.S. Estimated production capacity of these facilities is 2.24 billion gallons annually (NBB 2008). This thesis will later address the gap between actual biodiesel production and production capacity.

Characteristics of Biodiesel and Petroleum Diesel

Decades of research and practical application of biodiesel in diesel engines provide a wealth of data from which to evaluate engine performance, engine longevity and other factors of biodiesel. For the purpose of this study, it is important to compare and contrast the characteristics of each fuel. The following paragraphs describe attributes of biodiesel and petroleum diesel fuel.

In technical terms, fuel energy is measured in British Thermal Units (Btu), a measure defined as the amount of heat required to increase the temperature of one pound of water by one degree Fahrenheit. In relative terms, a gallon of 100 percent biodiesel has an energy content of 130,000 Btu, whereas a gallon of petroleum diesel’s Btu content is 140,000. This represents an energy deficit of about 9 percent (Hofman 2003). As a result, engines operating on 100 percent biodiesel (B100) produce 5-10 percent lower horsepower and torque, and achieve approximately 10 percent lower fuel economy figures. However, when biodiesel and petroleum diesel are blended using 20 percent biodiesel (B20), the energy deficit and corresponding horsepower, torque, and fuel economy reductions are about 3 percent, an amount almost unrecognizable to a vehicle operator.

Biodiesel possesses higher oxygen content than petroleum diesel, which partially accounts for the energy deficiency, yet translates to higher combustion efficiency. Combustion or ignition quality of all diesel fuels are rated with a scaled-number system called cetane number. Fuels with greater volatility have higher cetane number ratings. Biodiesel has a cetane number of 55, and petroleum diesel's cetane number is 48 (Hofman 2003). This difference is immaterial except as it pertains to reducing environmental pollutant emissions, which will be discussed later in this chapter. Worthy of note, however, is the lower flash-point of biodiesel versus petroleum diesel. Both fuels are much less volatile than gasoline, for example, which is flammable in both vapor and liquid forms. However, biodiesel's flash point, around 250 degrees Fahrenheit, is approximately double that of petroleum diesel (Purcella 2008, 80). This factor strongly favors biodiesel in terms of storage, transportation, and transfer of fuel from one container to another.

Biodiesel also provides superior lubricity versus petroleum diesel, particularly diesel fuels called Ultra-Low Sulfur Diesel (ULSD), which are mandated to replace commercial diesel fuel (DF-2) in the United States by 2010. Lubricity is defined as the ability to reduce friction of solid surfaces in relative motion (Schumacher 2006). Research indicates that removal of sulfur is not solely responsible for the reduced lubricity of ULSD fuel. Rather, the process of hydro-treating diesel fuel to reduce sulfur may alter the oxygen and nitrogen components of the fuel (Schumacher 2006). Lower lubricity in ULSD fuels may cause premature failure of engine components, particularly fuel injector pumps, as demonstrated in multiple iterations of independent testing (Schumacher 2006). Biodiesel maintains a high level of lubricity as an engine fuel. Biodiesel is also proven to increase lubricity of ULSD fuels when mixed in any percentage of fuel blends, even as low as 1 percent (NREL Guide 2006, 10). The greater lubricity properties of biodiesel fuel contribute to improved engine longevity by reducing wear on fuel delivery and internal engine components.

The fuel delivery system on a diesel engine consists of a fuel tank, fuel lines or hoses, a fuel filter, a mechanical or electronic fuel injection pump, and fuel injectors (Pahl 2007, 67). Biodiesel is compatible with each of these fuel delivery components, requiring no modification. Some tests and studies indicate, however, that some older vehicles (manufactured before 1993) experience seal deterioration or failure and fuel system leaks after switching to biodiesel or biodiesel blends. In most of these cases, the vehicles have nitrile or natural rubber components in the fuel delivery system, and are repaired by replacing them with synthetic or other non-rubber components (Hofman 2003).

Climatic Impacts on Biodiesel

Unlike gasoline, biodiesel and petroleum diesel fuels are both adversely affected by cold climate conditions. They will cloud, gel, and freeze in cold temperatures. There are three important definitions to know related to these conditions.

At approximately 20 degrees Fahrenheit (-7 degrees Celsius), petroleum diesel begins to cloud due to the formation of wax-like crystals. The term for this is cloud point. Fuel at this stage is visibly cloudy, but it has minimal effect on engine performance. Biodiesel begins to cloud at approximately 30 degrees Fahrenheit. The second term is called the cold filter plug point (CFPP). In this condition, fuel can clog filters, causing the engine to fail to start or stall during operation. CFPP normally occurs at a temperature ten degrees colder than the cloud point. The third and final term is the pour point. This term describes a condition where the fuel has gelled beyond the CFPP to the point where it will not flow through the fuel delivery system (NREL Guide 2006, 18).

Biodiesel made from varying feed-stocks have varying cloud points. An extreme example is biodiesel made from palm oil, which has a cloud point of 54 degrees Fahrenheit, and is therefore suitable only for tropical climates (Weyenburg 2007). Biodiesel made from used cooking oils or animal fats will cloud at higher temperatures than biodiesel made from virgin rapeseed or canola oil, but most biodiesel fuels reach their cloud point in the 30 degrees Fahrenheit range (Pahl 2007, 63). The table below indicates cloud point of various feedstock biodiesel fuels.

Table 1. Cloud Point of Biodiesel Fuel						
Test Method	Cloud Point ASTM D2500		Pour Point ASTM D97		Cold Filter Plug Point IP 309	
B100 Fuel	F	C	F	C	F	C
Soy Methyl Ester	38	3	25	-4	28	-2
Canola Methyl Ester	26	-3	25	-4	24	-4
Lard Methyl Ester	56	13	55	13	52	11
Edible Tallow Methyl Ester	66	19	60	16	58	14
Inedible Tallow Methyl Ester	61	16	59	15	50	10
Yellow Grease 1 Methyl Ester	--	--	48	9	52	11
Yellow Grease 2 Methyl Ester	46	8	43	6	34	1

Source: *National Renewable Energy Laboratory (NREL) Guide* (2006).

Fuel additives for cold weather climates used with petroleum diesel can also be used with biodiesel. These additives lower the cloud point of the fuel, improving cold-weather performance characteristics. Another technique for blended fuels is to decrease the biodiesel content during winter, and to use a higher biodiesel blend in warmer months.

In warm climates, biodiesel and petroleum diesel are both susceptible to bacterial growth in the fuel. The scientific names of the most common bacteria are *Cladosporium resinae* and *Pseudomonas aeruginosa* (Tickell 2003, 33). These occur naturally where favorable conditions exist, such as in a vehicle fuel tank or bulk storage container. Contributors are fuel, air, condensation, warmth, and absence of light. Bacteria in the fuel can be treated by adding biocides, which are available from fuel dealers and retail automotive parts stores (Pahl 2007, 64).

Biodiesel storage, transportation, and dispensing

No changes to existing fuel handling infrastructure are required for biodiesel (Pahl 2007, 59). The National Renewable Energy Laboratory (NREL) recommends that storage and transportation of biodiesel use the same precautions as those for petroleum diesel. Both fuels should be stored in clean, dry, dark containers made from aluminum, steel, fluorinated polyethylene, fluorinated polypropylene, Teflon™, or fiberglass (NREL Guide 2006, 27). Neither fuel should be stored for periods exceeding six months.

Both fuels are incompatible with some alloys, including brass, bronze, copper, lead, tin, and zinc. Presence of these in storage tanks may accelerate oxidation of the fuel and could potentially generate sediments causing premature fuel filter failure.

Biodiesel is safer to transport and store than petroleum diesel (Pahl 2007, 59). One reason is due to the lower flash-point of biodiesel mentioned previously. The second reason is that biodiesel is non-toxic and biodegradable (NREL Guide 2006, 1).

Biodiesel Fuel Standards and Quality

Product specifications and materiel standards are important for purposes of quality control. Austria was the first country to establish a biodiesel standard, in 1991. The measure, called ON C 1190, resulted from the successful production efforts by BLT and Silberberg College, and subsequent commercial production. As biodiesel production gained popularity across Europe, other European countries adopted their own biodiesel standards. For example, France and Italy established their standards in 1993, as did the

Czech Republic in 1994, and Germany in 1997. In 2003, the European Union (EU) adopted a measure drafted by the European Committee on Standardization (EU CEN) called EN 14214. This standard effectively supersedes all nationally adopted standards among EU member nations (Pahl 2007, 89).

In the United States, the American Society for Testing and Materials International (ASTM) is the authoritative body which represents technical standards for a broad range of materials, products, systems, and services (Purcella 2008, 45). Within ASTM, specifications for petroleum products and lubricants are maintained under ASTM Committee D02. This committee is comprised of fuel producers, engine equipment manufacturers and third parties, such as consumers and government agencies. Because of the diversity of committee members and the broad interests they represent, consensus to issue a standard can be arduous, sometimes taking as long as ten years. ATSM standards, for this reason, are recognized and adopted not only in the United States, but often worldwide.

ASTM D 975 is the U.S. diesel fuel standard. It prescribes numerous specifications or characteristics of the fuel, including flash point, cloud point, cetane number, acidity, plus water, sediment, and mineral content, among others.

ASTM began evaluation of alkyl-esters (biodiesel) in June, 1994. Five years later, ASTM approved a biodiesel standard, ASTM PS 121-99. In December, 2001, ASTM superseded it by issuing ASTM D 6751, which has since been the national recognized standard for biodiesel to be used for blends with petroleum diesel up to 20 percent (NBB 2008).

Biodiesel Use and the Environment

The environmental impact of biodiesel can be measured in terms of the production process and consumption or engine exhaust emissions. Documented research indicates that both are relatively benign in comparison to petroleum diesel. The paragraphs below describe the advantages of biodiesel relative to petroleum diesel fuel relating to production by-products and consumption emissions.

There are two significant by-products in the biodiesel production process. The first is glycerine, which has been chemically separated from the oil (transesterification), and the second is waste water from the fuel rinsing procedure.

Glycerine comprises approximately 10 percent of the production process, by volume (Pahl 2007, 87). In other words, producing ten gallons of biodiesel results in about one gallon of glycerine. The biggest hazard of glycerine is the methanol (grain alcohol) content remaining from the transesterification process. Recovery and recycling of methanol from the glycerine is possible, yet complex. Glycerine has many commercial and ecological uses. It can be used for making soaps and cleaners, as a livestock food additive, and as a humectant or dust abatement treatment. Glycerine is biodegradable, and is a good additive for composting and can be disposed of in public landfills (Purcella 2008, 171).

Wastewater results from the procedure of rinsing biodiesel to remove suspended material and other impurities. A major concern with disposal of wastewater is its high biochemical oxygen demand (BOD), which is a measure of the amount of oxygen used by aerobic bacteria during decomposition of organic matter (Wheeling Jesuit University 2008). Wastewater from large-scale commercial biodiesel producers requires pretreatment before it can be safely introduced to a municipal water treatment facility (Purcella 2008, 172).

Biodiesel production is much more ecologically advantageous than production of petroleum diesel. Citing a 1998 joint study by the U.S. Department of Energy and U.S. Department of Agriculture, author Greg Pahl states that "wastewater from the production of biodiesel is 79 percent lower than the overall production of wastewater from petrodiesel. What's more, the overall life-cycle production of hazardous solid wastes from biodiesel is 96 percent lower than overall production of hazardous solid wastes from diesel." (Pahl 2007, 58).

Numerous studies document the emissions of diesel engines burning biodiesel fuel. Combustion exhaust emissions research has been performed for many different diesel engine applications, from light automotive to heavy industrial vehicles. Data from these segments and other applications in-between are generally divided into two categories, on-road and off-road use. The U.S. Environmental Protection Agency (EPA) mandates diesel engine emissions standards and monitors industry/manufacturer compliance for both categories. The EPA regulated diesel engine emissions are total hydrocarbons (THC), nitrous oxides (NOx), carbon monoxide (CO), and particulate matter (PM). (NREL 2003, 2-1).

The evidence indicates appreciable reductions of THC, CO, and PM. For example, considering the lifecycle basis, these reductions could be as great as 78 percent for carbon dioxide and 46 percent for carbon monoxide (EPA 2002). These reduced pollutants make biodiesel an attractive alternative fuel. However, one EPA regulated emission, nitrous oxide (NOx), actually exhibits a nominal increase with biodiesel (EPA

2002). The table below summarizes the percentage change in diesel engine emissions for EPA regulated emissions.

Table 2. Percentage Change in EPA Regulated Emissions of Diesel Engines							
Engine Type/ Model Year	Fuel Pair	Engines	NOx	PM	CO	THC	THC+PM
20 Percent Biodiesel Emission Effects							
2-Stroke<1991	D-2/B20	6	3.2%	-1.8%	-13.9%	-20.9%	-14.8%
2-Stroke 1991+	D-2/B20	2	3.9%	-17.8%	-12.0%	-17.5%	-17.6%
4-Stroke<1991	D-2/B20	3	2.9%	-15.7%	-13.6%	-12.2%	-13.5%
4-Stroke 1991-3	D-2/B20	4	-0.9%	-15.7%	-12.0%	-2.8%	-12.0%
4-Stroke 1994+	D-2/B20	5	2.8%	-9.8%	-15.2%	-24.0%	-19.2%
Overall Average	D-2/B20	20	2.5%	-9.0%	-13.3%	-18.2%	-15.1%
100 Percent Biodiesel Emission Effects							
2-Stroke 1991+	D-2/B100	1	19.6%	-33.0%	-42.4%	-72.7%	-59.2%
4-Stroke 1991-3	D-2/B100	2	13.3%	-68.3%	-41.8%	-38.7%	-58.8%
4-Stroke 1994+	D-2/B100	5	9.9%	-36.6%	-41.5%	-76.3%	-62.8%
Overall Average	D-2/B100	8	11.8%	-51.0%	-42.0%	-69.7%	-61.5%

Source: EPA, *Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions* (October 2002).

This section of the literature review described the characteristics of biodiesel and provided some comparisons with petroleum diesel fuel with respect to several tangible considerations. Biodiesel emerges favorably in most cases under this context. The literature review indicated, however, that additional factors should be considered. These factors are more difficult to measure, yet important in the social and political context surrounding biofuels in general and biodiesel specifically.

Other Biodiesel Considerations

Despite the recognized advantages of biofuels in general, and biodiesel in particular, there has been much concern about potentially harmful impacts. One consideration addresses the question of energy value, and suggests that the energy and resources consumed to produce biofuels are greater than the energy content ultimately derived from the alternative fuels. A second consideration addresses the risk of producing energy crops versus food crops, and asks whether or not it has an adverse impact on food supplies and prices.

The first issue is addressed by what is called the energy efficiency ratio. "This is a numerical figure that represents the energy stored in the fuel compared to the total energy required to produce, manufacture, transport, and distribute the fuel." (Pahl 2007, 58) Calculating an energy efficiency ratio follows the EIA's "comprehensive approach" to take all energy into account (EIA, found at http://www.eia.doe.gov, accessed 4 August 2008). The 1998 DOE/USDA study found that biodiesel and petroleum diesel are very similar, each with a negative efficiency ratio of .80:1 and .83:1, respectively (DoE 2008). Where the difference becomes more pronounced is when all but fossil energy factors are subtracted. "In terms of effective use of fossil energy resources, biodiesel yields around 3.2 units of fuel product for every unit of fossil energy consumed in the lifecycle. By contrast, petroleum diesel's life cycle yields only .83 units of fuel product per unit of fossil energy consumed" (DoE 2008). Some studies since 1998 reached different conclusions regarding biodiesel's energy efficiency ratio. Figures vary, but the evidence indicates that biodiesel generally provides more energy than petroleum diesel on a lifecycle basis (Pahl 2007, 58).

The second issue, the purported impact of converting traditional food crops such as corn and soybeans to fuel versus food, remains contentious in current literature. The debate is center stage among national policy and legislative bodies, especially in those nations that are increasing production of biofuels. The United Nations World Food Program (WFP) cites four factors contributing to increased food prices. One factor is "farmers start to grow biofuels crops leading to a reduction in the production of food," (WFP 2008). The WFP also identifies rising fuel costs as the primary contributor, which is the consensus among the majority of fuel-food related studies. "The global food system is heavily dependent on petroleum, not just for shipping goods from one location to another but also for production, packaging, and processing. As the price of oil rises, so do the costs of planting, harvesting, and delivering food" (Lapidos 2008).

Ethanol is the primary focus of this food-or-fuel debate. But all biofuels, including biodiesel, are implicated and therefore should be investigated. Numerous government and private research reports refute claims that biofuels production negatively impacts food production (Urbanchuk 2008). In June, 2008, the Department of Energy (DOE) presented testimony to the U.S. Senate Committee on Energy and Natural Resources. DOE's testimony indicated that figures are often misleading. An example is the fact that in 2007, some 25 percent of the U.S. corn crop was dedicated to biofuels production. However, one-third of that amount was recovered for other purposes, such as livestock feed. "Thus, in actuality, only about one-sixth of the U.S. corn crop by mass is used in fuel production," said DOE's Alexander Karsner, Assistant Secretary for Energy Efficiency and Renewable Energy. Karsner continued by saying that U.S. corn exports were steady over the past decade, and actually increased recently (DOE 2008).

The concerns of biofuel critics regarding the energy value and impact on food supplies and prices are prominent in current literature and news media, but based on available research, their analysis is largely unsubstantiated. The ratio of energy efficiency of biodiesel when compared to petroleum diesel is proven positive, and the suggestion that biofuel crops infringe upon production of food crops oversimplifies a complex problem.

To summarize this section, the literature review introduced numerous considerations regarding biodiesel pertaining to fuel characteristics and climatic, environmental and social factors. The literature consistently shows that biodiesel is a reliable, efficient, environmentally sound alternative to petroleum diesel. While not a perfect alternative, the literature suggests that biodiesel used in blends with petroleum diesel is viable for diesel-powered vehicles, including tactical vehicles, and warrants further investigation. The following studies address key criteria regarding the use of biodiesel in tactical vehicles, and the support and interest in biodiesel among large diesel vehicle fleet operators.

Case Studies

The TECOM Experiment

This study, *Biodiesel Fuel Evaluation for the U.S. Army Tactical Wheeled Vehicles*, was conducted by the U.S. Army Test and Evaluation Command (TECOM) at the U.S. Army Yuma Proving Grounds (YPG) from March 1994 to March 1995. TECOM conducted the evaluation with two objectives--first, to “collect data to evaluate the relative performance of an 80/20 JP-8/biodiesel fuel mixture when compared to neat (100 percent) JP-8 and DF-2 (commercial diesel fuel) in different wheeled vehicle systems," and second, to "accrue endurance mileage while operating with a 80/20 JP-8/biodiesel fuel mixture on different vehicle engines and fuel systems so any failures related to the biodiesel fuel mixture can be ascertained" (TECOM 1995, 1).

Fourteen vehicles comprised the test fleet, which included three M1028 Commercial Utility Cargo Vehicles (CUCV), five M1037/1038 High Mobility Multi-Purpose Wheeled Vehicles (HMMWV), three M939A2 5-ton trucks, and three M985 Heavy Expanded Mobility Tactical Trucks (HEMTT). These vehicles, except CUCVs, accumulated over 163,000 miles of mission profile endurance operations during the one year test period, consuming over 26,000 gallons of biodiesel blended fuel.

The TECOM evaluation performed four tests. These tests were engine exhaust smoke opacity measurement, acceleration, drawbar pull, and endurance operation. The following paragraphs describe the testing methods and procedures.

Engine Exhaust Smoke Opacity Sub-test

Exhaust smoke opacity readings indicate the quantity of solid particulate matter in engine exhaust. Exhaust gases are measured by an opacity meter attached to the vehicle exhaust pipe. TECOM's evaluation employed a Wager model 650A opacity meter. Samples were taken for each vehicle while stationary with engines operating at low revolutions per minute (rpm) (idle speed), medium rpm (approximately 1,500 rpm), and high rpm (approximately 2,200-3,000 rpm). Additionally, snap-idle measurements were taken. Snap-idle is the standard measurement technique to achieve a peak condition as described by Federal emission regulations. It is accomplished by fully depressing the accelerator pedal for 1-2 seconds, and then releasing the pedal to resume idle speed. Samples included operating on only JP-8, only DF-2, and blended JP-8/biodiesel.

Acceleration Sub-test

Acceleration and speed characteristics were measured for each vehicle on the YPG Dynamometer Course using a Campbell Scientific Data Recorder. Vehicles started from a stationary position, operated with full throttle until achieving the maximum speed. Time increments were recorded for each 5 miles-per-hour (mph) interval from zero to maximum speed. Six iterations were performed and results for each vehicle were averaged. The acceleration sub-test was conducted with each vehicle operating on only JP-8, only DF-2, and blended JP-8/biodiesel, except the CUCV which was not tested using DF-2.

Drawbar Pull Sub-test

Drawbar pull is a technique to calculate a vehicle's horsepower, in excess of that required for vehicle propulsion on a level road, for acceleration, climbing grades, and towing objects such as another vehicle or a trailer. Drawbar pull was measured by coupling the test vehicle to a mobile field dynamometer vehicle equipped with a calibrated load cell. Each vehicle was tested using low-range single and multiple gear selector configurations ("first" and "drive" on automatic transmissions). The test was performed starting from stationary and applying full throttle. Instruments recorded drawbar pull horsepower, load cell weight, and engine rpm at one mph road speed increments, up to the safe operating speed of the mobile field dynamometer. The drawbar pull sub-test was conducted with each vehicle operating on only JP-8, only DF-2, and blended JP-8/biodiesel, except the CUCV, which was not tested using DF-2. The study did not indicate the number of pull iterations recorded.

Endurance Operation Sub-test

Vehicles operated on a 200-mile course over varying surface conditions, including paved primary roads, gravel secondary roads, unimproved trails, and cross-country. Each surface condition was a percentage of the total mileage in accordance with the vehicle's operational profile. For example, the CUCV course was 20 percent paved primary road, 50 percent gravel secondary road, 15 percent cross-country, and 15 percent unimproved trail. The HMMWV course was 30 percent paved primary road, 30 percent gravel secondary road, and 40 percent cross-country. The 5-Ton Truck course was 30 percent paved primary road, 28 percent gravel secondary road, and 42 percent cross-country. The HEMTT course was 15 percent paved primary road, 75 percent gravel secondary road, and 10 percent cross-country. The study did not state the number of course iterations conducted. It did indicate, however, that additional mileage was accrued using the YPG Mechanical Reliability Course, and that total accumulated mileage of the fourteen test vehicles was 163,954 miles. The endurance operation sub-test was performed exclusively with biodiesel blended fuel. TECOM recorded preventive or corrective maintenance actions throughout the test for each vehicle. A summary of that record is presented in Appendix A of this study.

The ASG Survey

This study, *Biodiesel End User Survey*, was conducted by ASG Renaissance of Dearborn, Michigan in 2003. The survey was commissioned by the National Biodiesel Board and its purpose was to obtain information from diesel fleet managers regarding fuel preferences. ASG Renaissance completed the survey report in February, 2004.

Survey participants were identified via original equipment manufacturers (OEM) customer lists, trade association membership lists, the National Biodiesel Board, and diesel event attendees. ASG Renaissance conducted the survey through telephone interviews, achieving a 71 percent response rate with fifty responses to seventy contacts. Respondents represented 50,821 diesel-powered vehicles, with an average fleet size of 550 units. While the survey is not a random sample of all fleets, the survey is representative of Class II to Class V (based on gross vehicle weight) vehicle registrations by OEM. These consisted of multiple OEM manufacturers, providing a cross section of brands and vehicle operating profiles to qualify user responses.

Synthesis of these study results constitute one portion of the data used for this thesis. The author expects findings from these case studies to support the secondary thesis questions specific to vehicle performance and fuel characteristics. The synthesis is presented in chapter 4.

Summary

Chapter 2 presents the review of current literature regarding biodiesel. It provides a background summary of the history of biodiesel research and development, and describes the fuel's characteristics, including advantages and disadvantages relative to considerations such as climate and environmental impacts. This chapter provides data regarding commercial biodiesel production, and addressees some contentious factors concerning biodiesel use. Finally, chapter two presents two case studies which form a portion of the data for analysis in support of the thesis question. The following chapters describe the study methodology, analysis, and conclusions.

CHAPTER 3

RESEARCH METHODOLOGY

Introduction

The purpose of this thesis is to determine whether it is feasible to use biodiesel to fuel U.S. Army tactical vehicles within the continental United States (CONUS). The literature review in the preceding chapter provides a background to the origin and evolution of biodiesel, and its gradual acceptance in civilian and government applications as an alternative to petroleum diesel. The available literature also reveals a relative lack of research specific to biodiesel use in military tactical vehicles. This study attempts to fill that gap by synthesizing findings from two research studies, and by determining the quantity of biodiesel required to implement biodiesel use in U.S. Army tactical vehicles within CONUS.

Description

This chapter presents the secondary research questions and describes the research methodology employed in the study. The primary research question remains: is it feasible to use biodiesel to fuel U.S. Army tactical vehicles within the continental United States (CONUS)? The secondary questions to be addressed are:

1. Does biodiesel-blended fuel cause any greater incidence of engine malfunction than JP-8 when used in U.S. Army tactical vehicles?

2. Does biodiesel-blended fuel require modification to the U.S. Army's existing fuel storage and distribution infrastructure?

3. What quantity of biodiesel is required to displace a portion of the U.S. Army's (CONUS) annual JP-8 requirement?

The methodology employed in this study is a mixed approach, combining qualitative and quantitative data. The methodology employs two distinct processes, each comprised of several steps.

The first process is synthesis of primary research findings, and the second is quantity gap analysis. The first and second research questions are addressed by the synthesis process.

1. Does biodiesel-blended fuel cause any greater incidence of engine malfunction than JP-8 when used in U.S. Army tactical vehicles?

2. Does biodiesel-blended fuel require modification to the U.S. Army's existing fuel storage and distribution infrastructure?

The synthesis process follows four sequential steps; selecting data sources, analyzing separate source findings, synthesizing findings between the sources, and forming conclusions.

The selected two sources are the U.S. Army Test and Evaluation Command (TECOM) study and the ASG Renaissance (ASG) survey. The TECOM study, entitled Biodiesel Fuel Evaluation for the U.S. Army Tactical Wheeled Vehicles, is an objective biodiesel experiment using U.S. Army tactical vehicles. It provides quantitative data and analysis to answer the secondary research questions. The Biodiesel End User Survey, produced by ASG-Renaissance, is the largest survey about biodiesel user satisfaction identified in the literature review. It encompasses over 50,000 diesel-powered vehicles, and provides quantitative and qualitative data to answer the secondary research questions.

Synthesis of data occurs where corroborative evidence exists between these two studies, specific to incidents of engine malfunction and biodiesel-blended fuel storage, handling, and dispensing.

To address the third research question (what quantity of biodiesel is required to displace a portion of the U.S. Army's (CONUS) annual JP-8 requirement?), this study performs a biodiesel production gap analysis in four steps. First, the research establishes an optimal biodiesel blend for use in tactical vehicles. Second, the research geographically divides CONUS to enable calculation of fuel quantities by region versus the continental United States as a whole. Because climate affects some biodiesel characteristics, this study dissects CONUS by latitude into three regions--South, Central, and North. Next, the study compares figures regarding biodiesel production, biodiesel production capacity, and U.S. Army JP-8 requirements within those regions. Finally, this study estimates the quantity of biodiesel required to implement an optimal fuel blend within each of the defined three regions of CONUS.

Optimal Biodiesel Blend

ASTM D-6751 is the American biodiesel standard, and it applies specifically to a 20 percent blend of biodiesel with petroleum diesel. This is the standard approved by the Environmental Protection Agency (EPA) and promoted by the National Biodiesel Board (NBB) (NBB 2008). Further, a 20 percent biodiesel blend is the specified blend for use in General Services Administration (GSA) fleet vehicles operated by all agencies of the Federal Government (Commercial Item Description A-A-59693A 2009). The TACOM study utilized a 20 percent biodiesel blend, and the ASG survey further indicated that this blend is predominant among commercial and private diesel-vehicle fleet operators who use biodiesel-blended fuel. For these reasons, a 20 percent biodiesel blend is the optimal blend for purposes of this thesis.

Regions within CONUS

Prior research for this study indicated that biodiesel is not produced in sufficient quantities to displace a high percentage of JP-8 simultaneously across all of CONUS. A method of dividing CONUS into regions is necessary to assess the feasibility of an incremental implementation concept.

Federal agencies and departments use numerous geographic dissections of the continental United States. Within the Department of the Army, Army Commands (ACOMs) use geographic regions to define boundaries for various purposes. For example, U.S. Army Training and Doctrine Command (TRADOC) used seven regions, labeled A through G, to delineate responsibilities of The Army School System (TASS) (Global Security 2009) prior to transformation and reorganization decisions in 2005 and 2008 (National Guard Bureau, 2008).

Installation Management Command (IMCOM), a subordinate command of Army Materiel Command (AMC), as another example of geographic dissection, uses three regions--Northeast, Southeast, and West, for administrative purposes (IMCOM 2009).

Because climate affects some biodiesel characteristics, this study dissects CONUS by latitude into three regions--South, Central, and North. While climate is a factor in implementing biodiesel use, this manner of presentation is not meant to lead the reader to conclude that biodiesel is not suitable for use in the predominantly colder northern climates. Figure 2 illustrates the regions defined for this study. Dividing CONUS generally along lines of latitude enables definition of regions and calculations of fuel requirements for the purposes of this thesis.

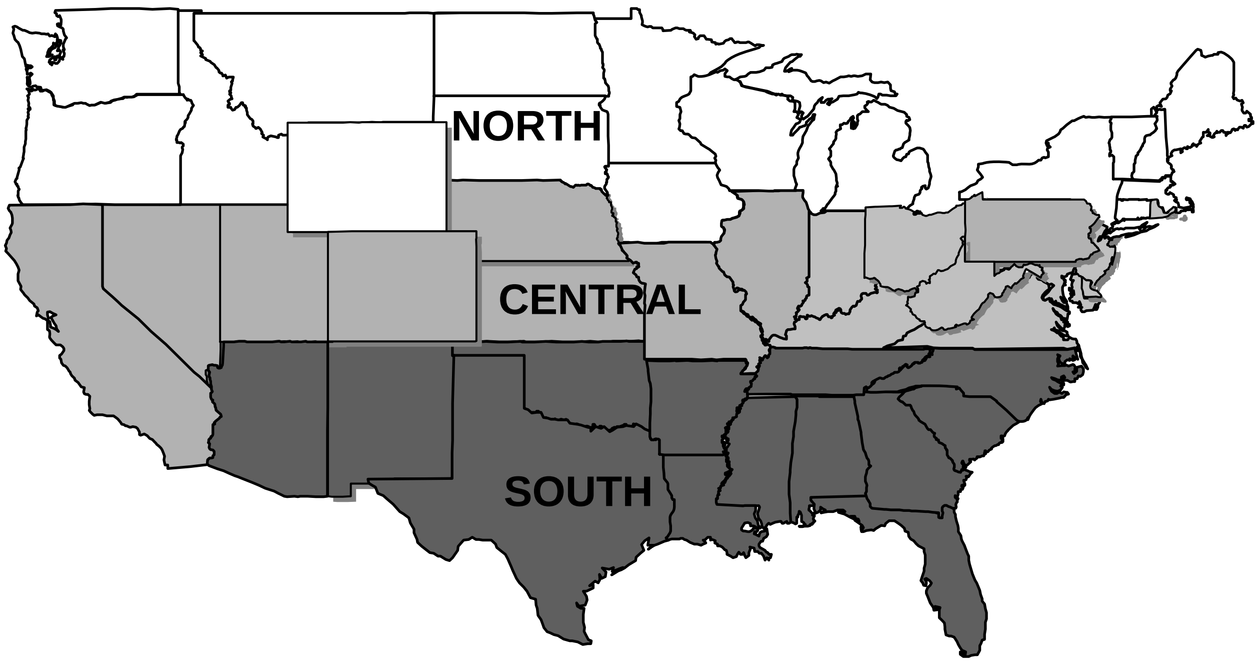

Figure 2. CONUS Regions used for this study
Source: National Guard Bureau, presentation titled "ARNG BCT's", dated 22 JUL 2008. It was created in the Operations Division of the G-3 Directorate

CONUS JP-8 Requirement

JP-8 requirements for each region are calculated in two steps. First, dividing the total CONUS JP-8 fuel requirement by the number of CONUS-based tactical organizations results in a fuel requirement per tactical organization, or quotient. The tactical organization or unit of measure is the Brigade Combat Team (BCT)--BCTs are the Army's modular war-fighting organizations, and are organized in three variants--

Heavy Brigade Combat Teams (HBCT), Infantry Brigade Combat Teams (IBCT), and Stryker Brigade Combat Teams (SBCT).

According to the 2006 Army Campaign Plan (ACP), there are seventy BCTs in the United States Army (Army Campaign Plan 2006). As of 2006, 63 BCTs are CONUS-based, including 28 Army National Guard BCTs. Seven BCTs are based in Germany, South Korea, Italy, Alaska, and Hawaii. In addition to the BCT, the U.S. Army contains 221 functional brigades and multi-functional brigades. Examples of functional and multi-functional brigades include the Fires Brigades, Battlefield Surveillance Brigades, Sustainment Brigades, and Maneuver Enhancement Brigades. Of these types of brigades, 75 are Active Component, and 136 are Reserve Component (ACP 2006).

This thesis makes three assumptions relative to determining the U.S. Army CONUS JP-8 requirement. These assumptions are necessary for estimating biodiesel requirements. The first assumption is that geographic distribution of functional and multi-functional brigades is similar to BCTs, meaning that ninety percent of these brigades are CONUS-based. Further, the second assumption is that within CONUS, these functional and multi-functional brigades are distributed within the three defined CONUS regions, proportional to the BCTs. Finally, this study acknowledges that fuel requirements differ between different brigade types. Even among BCTs, fuel requirements vary based upon the number and type of vehicle systems organic to each type of brigade, and the operational tempo of any particular brigade. The final assumption, therefore, is that the BCT is representative of all brigades for the purpose of averaging fuel requirements within a large geographic region.

The second step to determine JP-8 fuel requirements by CONUS region is to multiply the number of BCTs within each region by the quotient of step one. The product is the JP-8 fuel requirement for each region. The location of each of the U.S. Army's sixty-three CONUS-based BCTs is depicted in Table 3.

Table 3. CONUS-based U.S. Army Brigades by Region, as of 2006

REGION	Number of BCTs
NORTH	14
CENTRAL	25
SOUTH	24

Source: Created by author.

Quantity Gap Analysis

The quantity gap analysis compares the figures for total national biodiesel production, national biodiesel production capacity, and the U.S. Army's JP-8 requirement within three geographic CONUS regions. A simple table is used to illustrate the figures and facilitate the comparison. If the total national biodiesel production equals or exceeds 20 percent of the JP-8 fuel requirement for any of the three regions, this is considered a significant finding. Similarly, if the total national biodiesel production capacity equals or exceeds 20 percent of the JP-8 fuel requirement for all three of the defined regions, this is considered a significant finding. Significant findings are considered to affirm the feasibility of using biodiesel in U.S. Army tactical vehicles within CONUS.

Summary

This chapter describes the research method used in this study, to determine an answer to the primary thesis question of whether it is feasible to use biodiesel to fuel U.S. Army tactical vehicles within the continental United States (CONUS).

This study uses a mix of qualitative and quantitative data to answer three secondary research questions:

1. Does biodiesel-blended fuel cause any greater incidence of engine malfunction than JP-8 when used in U.S. Army tactical vehicles?

2. Does biodiesel-blended fuel require modification to the U.S. Army's existing fuel storage and distribution infrastructure?

3. What quantity of biodiesel is required to displace a portion of the U.S. Army's (CONUS) annual JP-8 requirement?

Information from two primary source findings, the TECOM study and the ASG survey, is synthesized to answer research questions one and two regarding diesel engine performance and biodiesel storage. The third research question regarding biodiesel quantity is answered by analyzing a data table, created by the author, which depicts JP-8 requirements within three CONUS regions and biodiesel production. The technique employed is gap analysis, focused to determine biodiesel production sufficient to implement an optimal biodiesel blend for U.S. Army tactical vehicles within CONUS. The result of this methodology is presented in chapter 4.

CHAPTER 4

ANALYSIS

Introduction

Chapter 1 described the issues which provide the impetus to perform this study. The prominence of oil and petroleum products, in American society and the American military, pose a potential national security risk. Oil production is peaking and declining in numerous countries, while production escalates in other regions to maintain stability and meet global demand. The prospect of exhausting petroleum resources puts American security interests in peril.

Current U.S. Army tactical vehicles, and those to be fielded in the foreseeable future, rely upon petroleum-derived fuel for their internal combustion diesel engines. A large body of research has been performed in the past 30 years using biodiesel to fuel diesel engines and the multitude of vehicles they propel, including trucks, tractors, trains, and ships. Little of that research, as revealed in the literature review, focused on military tactical vehicles. This study is important because an information gap exists in open-source research. The gap resides between one field within the body of biodiesel literature (civilian-private, civilian-commercial, and governmental-public) and another field (governmental-military). This study aims to fill that gap in two ways. First, it attempts to correlate information from the available non-military literature to tactical vehicle applications. Second, this study determines the requisite quantity of biodiesel to displace a percentage of petroleum-based fuel consumed in U.S. Army tactical vehicles based within the continental United States (CONUS).

The purpose of the thesis, therefore, is to determine the feasibility to fuel U.S. Army tactical vehicles within CONUS with biodiesel.

Chapter 3 described the methodology employed in this study, which used quantitative and qualitative data from two sources, and a quantitative comparison of U.S. Army CONUS JP-8 fuel requirements and national biodiesel production. Chapter 4 presents separate source findings (U.S. Army Test and Evaluation Command (TECOM) *Biodiesel Fuel Evaluation for the U.S. Army Tactical Wheeled Vehicles* experiment and the ASG Renaissance (ASG) *Biodiesel End-User Survey*) and synthesizes these data to answer the following secondary research questions:

1. Does biodiesel-blended fuel cause any greater incidence of engine malfunction than standard diesel fuel (JP-8) in U.S. Army tactical vehicles?

2. Does biodiesel-blended fuel require modification to the U.S. Army's existing fuel storage and distribution infrastructure?

Additionally, this chapter presents the results of the quantity gap analysis to answer the remaining research question:

3. What quantity of biodiesel is required to displace a portion of the U.S. Army's (CONUS) annual fuel (JP-8) requirement?

The findings to these research questions form the basis for the study's conclusions and recommendations presented in Chapter 5.

Separate Source Findings

U.S. Army TECOM Biodiesel Experiment

The U.S. Army TECOM evaluation performed four tests, comparing tactical vehicle performance using JP-8, DF-2, and biodiesel-blended fuel. These tests measured engine exhaust smoke opacity, and the vehicles' acceleration, drawbar pull, and endurance operation. The following paragraphs present the findings and relevance of each sub-test.

Engine Exhaust Smoke Opacity Measurement

Opacity readings measure the solid particulate matter in engine exhaust gases. Readings were taken for each vehicle prior to changing the original fuel (DF-2) to the biodiesel-blended fuel. These initial samples established a baseline from which a deviation was measured. A second reading was taken immediately after the fuel change occurred. Subsequent readings were taken over time to measure biodiesel effects on engine exhaust gases.

Seven vehicles were measured with DF-2 fuel and subsequently with the biodiesel-blended fuel. TECOM found that all vehicles exhibited a reduced opacity reading, indicating a reduction of solid particulate matter in the exhaust. The immediate effect represented up to 76 percent reduction in engine exhaust particulate matter. TECOM also noted that for three specific vehicles (one High Mobility Multi-purpose Wheeled Vehicle-HMMWV, and two Heavy Expanded Mobility Tactical Trucks-HEMTTs), the opacity readings continued to decline in subsequent samples as vehicle mileage accrued. These three vehicles' final opacity readings with biodiesel-blended fuel were 46 percent, 40 percent, and 84 percent lower, respectively. Table 4 illustrates the exhaust smoke opacity test results. These findings are significant for three reasons. First, they are consistent with the data found in the literature review regarding the emission-reducing qualities of biodiesel-blended fuel. Second, these findings indicate that the particulate emission-reducing effects of biodiesel are immediate upon diesel engines.

Finally, these findings are significant because they document the continued reduction of particulate emissions from diesel engines over time when using biodiesel-blended fuel.

Table 4. Engine Exhaust Opacity Comparison

Vehicle Model	Identification Number	Fuel	Test Miles	AVG Opacity Reading (%) at Engine Condition			
				Idle	Medium	High	Snap
M1037 HMMWV	NG2BL3	DF-2	0	14	2	1	11
		Bio	0	3	2	1	6
			2365	1	1	1	11
			5856	9	1	3	7
	NG2BL1	DF-2	0	1	2	13	25
		Bio	0	1	1	1	13
			3431	3	1	1	12
			5370	5	0	1	9
M1036 HMMWV	NG2R35	DF-2	0	5	1	1	17
		Bio	0	1	0	0	4
			2419	3	1	2	8
			6249	3	1	1	8
M923A2 5-Ton	NLOZPP	DF-2	0	5	5	1	9
		Bio	0	3	4	3	8
M985 HEMTT	NPO6D8	DF-2	0	4	2	3	57
		Bio	0	3	1	3	46
			2717	2	1	2	48
			6636	0	1	2	32
			10026	0	1	1	22
	NPO6D8	DF-2	0	6	2	2	7
		Bio	0	3	1	1	3
			2785	4	1	3	4
			5792	2	1	0	3
			10181	2	0	1	2
	NPOEA4	DF-2	0	4	3	10	35
		Bio	0	2	2	4	25
			1824	2	1	4	23
			6215	2	5	2	22
			102237	6	1	2	21

Source: U.S. Army, *Biodiesel Fuel Evaluation for the U.S. Army Tactical Wheeled Vehicles* (U.S. Army TECOM 1994).

Acceleration

The acceleration sub-test measured speed characteristics of vehicles using different fuels. It was conducted with each vehicle using JP-8, DF-2, and biodiesel-blended fuel, except the Commercial Utility Cargo Vehicle (CUCV) which was not tested using DF-2. No explanation was provided as to why the CUCV was not tested using DF-2. TECOM performed six iterations of the acceleration sub-test, and results for each vehicle were averaged.

TECOM concluded that acceleration improved when using biodiesel-blended fuel versus JP-8 in the CUCV, HMMWV, HEMTT, and M915A2 Truck Tractor. The range of improvement was between .2 percent and 6.8 percent. For the M999 5-ton truck, the acceleration was deemed equal when using biodiesel-blended fuel and JP-8. When vehicle acceleration was compared between biodiesel-blended fuel and DF-2, acceleration was lower on the biodiesel-blended fuel for all vehicles. The range of decreased acceleration was between 11 percent and 14.5 percent. TECOM attributed this result to the greater energy content of DF-2 versus JP-8. The energy content of biodiesel exceeds that of JP-8, but is less than that of DF-2. Table 5 illustrates the combined results of the acceleration subtest. The findings of the acceleration sub-test are important because they establish parity between JP-8 and biodiesel-blended fuel in this engine performance criterion.

Table 5. Acceleration Comparison				
Vehicle Type	**Fuel Type Biodiesel Blend Compared to:**			
	JP-8		**DF-2**	
	Acceleration Time Change	**Amount (%)**	**Acceleration Time Change**	**Amount (%)**
CUCV	Decrease	6.8	N/A	N/A
HMMWV	Decrease	1.2	Increase	11.3
5-Ton	Equal	0	Increase	11
HEMTT	Decrease	5.6	Increase	12.8
M915A2	Decrease	0.2	Increase	14.5

Source: U.S. Army, *Biodiesel Fuel Evaluation for the U.S. Army Tactical Wheeled Vehicles* (U.S. Army TECOM, 1994).

Drawbar Pull

The drawbar pull sub-test measured each vehicle's horsepower, in excess of that required for vehicle propulsion on a level road, for acceleration, climbing grades, and towing objects such as another vehicle or a trailer. TECOM conducted this test with each vehicle using JP-8, DF-2, and biodiesel-blended fuel, except the CUCV, which was not tested using DF-2. No explanation was provided as to why the CUCV was not tested using DF-2. Also, each vehicle was tested using two drive-gear configurations, low-range single and low-range multiple gears ("first" and "drive" on automatic transmissions). The study did not indicate the number of test iterations recorded.

TECOM found that draw-bar pull capabilities increased generally when vehicles were operated with biodiesel-blended fuel versus JP-8. Exceptions were the M923 5-ton truck when operated in low-range first gear, and the HEMTT when operated in both drive gear configurations. As a percentage of horsepower change compared to JP-8, TECOM's findings represent horsepower decreases of .7 percent, 3.4 percent, and .2 percent respectively for those vehicles. Compared to JP-8, using biodiesel-blended fuel resulted in increased draw-bar pull horsepower for all the other test vehicles. The increase ranged from .3 percent to 8.6 percent. Contrarily, results of biodiesel-blended fuel compared to DF-2 diesel fuel show decreased draw-bar pull horsepower for all test vehicles. This result included both drive-gear configurations. The decrease, as a percentage, ranged from 6.2 percent to 19.2 percent. TECOM concluded, again, that this comparison result was expected due to the relative energy content disparity between JP-8, biodiesel-blended fuel, and DF-2. Table 6 illustrates the combined results of the draw-bar pull subtest.

The drawbar pull sub-test measured another engine performance criterion, and like the acceleration sub-test, these findings establish parity between biodiesel blended-fuel and JP-8 in the sample vehicles.

Table 6. Drawbar Pull Comparison					
Vehicle Type	Gear	Fuel Type Biodiesel Compared To:			
		JP-8		DF-2	
		DBP Change	Amount (%)	DBP Change	Amount (%)
CUCV	First	Greater	3.4	N/A	N/A
	Drive	Greater	8.6	N/A	N/A
HMMWV	First	Greater	0.6	Less	11.5
	Drive	Greater	0.9	Less	19.2
5-Ton	First	Less	0.7	Less	9.5
	Drive	Greater	0.3	Less	10.1
HEMTT	First	Less	3.4	Less	9.7
	Drive	Less	0.2	Less	7.8
M915A2	First	Greater	2.7	Less	6.2
	Drive	Greater	2.3	Less	12.4

Source: U.S. Army, *Biodiesel Fuel Evaluation for the U.S. Army Tactical Wheeled Vehicles* (U.S. Army TECOM 1994).

Endurance Operation

The endurance operation sub-test was the only TECOM test performed exclusively with biodiesel-blended fuel, so there is no comparison data for JP-8 or DF-2 diesel fuels. All test vehicles operated on DF-2 diesel fuel prior to introducing the biodiesel-blended fuel. When TECOM changed the fuel, they drained fuel tanks and replaced fuel filters. TECOM did not flush vehicle fuel systems. Vehicles in this sub-test were operated on a 200-mile course over varying surface conditions including paved primary roads, gravel secondary roads, unimproved trails, and cross-country. The report did not indicate the number of course iterations performed.

TECOM recorded preventive and corrective vehicle maintenance actions performed during the sub-test, and that data formed their basis for several conclusions. First, TECOM recognized the relative solvent qualities of the three fuels. Biodiesel is a greater solvent than JP-8, which is a greater solvent than DF-2. For this reason, test vehicles exhibited some fuel delivery system problems, such as leaks. TECOM summarized that these problems emerged due to the solvent qualities of the fuel, and were consistent with “observations from Operation Desert Storm when JP-8 fuel replaced DF-2 in tactical vehicles” (TECOM 1994, 3). Test personnel implemented a policy to change fuel filters within 300-500 miles of the fuel change over, allowing the biodiesel blended fuel to cleanse the vehicle fuel systems. Fuel filters captured dissolved fuel system deposits, consequently reducing further incidents.

TECOM noted that four major fuel system components failed on four separate vehicles during the test, including three fuel pumps and one fuel injector. Two fuel pumps were on CUCVs, one on a HMMWV, and the fuel injector was on a HMMWV. The CUCV fuel pumps were replaced due to leaks, even though the units had relatively low mileage. TECOM attributed the leaks to vehicle age (both were manufactured in 1986), speculating that the leaks potentially resulted from the combined effects of the increased solvency of biodiesel-blended fuel and deteriorated internal seals. Cause could not be determined on the HMMWV fuel pump failure nor the HMMWV fuel injector failure. TECOM suspected that a constricted fuel filter was to blame in the former, limiting the fuel flow through the pump thereby reducing lubrication of internal parts.

Eight vehicles exhibited lower engine idle speeds following change over to the biodiesel-blended fuel. Lower idle speed and smoother idle are two conditions consistent with the findings of the literature review. In TECOMs experiment, idle speed adjustments corrected the issues in all cases, initially. Two of these eight vehicles subsequently exhibited similar engine performance issues. TECOM described one as "stalling" and another as "running rough." Changing fuel filters corrected both.

Four fuel hose leaks were observed and recorded throughout the duration of the endurance operations sub-test. TECOM attributed these to the increased solvency of the biodiesel-blended fuel, and its propensity to dissolve solids such as accumulated dirt and dust at fuel line junctions and around fastening hardware.

TECOM made a general observation that test vehicles with initial higher mileage experienced greater frequency of fuel system faults when using biodiesel blended fuel. Specifically, HMMWVs had the highest average mileage. CUCVs, 5-ton trucks, and HEMTTs had comparatively low average miles when the test commenced.

During the endurance operation sub-test, greater than one out of four (28 percent) vehicles showed no fuel system or engine faults. Excluding idle adjustments following fuel changeover, 77 percent exhibited only one fault per vehicle requiring corrective action. Using that same exclusion, only two vehicles (14 percent) exhibited three or more faults during the endurance operation sub-test using biodiesel-blended fuel.

Including all recorded faults, and distinguishing between vehicle types, HMMWVs exhibited the highest number of faults per vehicle, averaging 2.6 incidents. HEMTTs exhibited the fewest faults per vehicle, averaging less than one incident. Table 7 summarizes the recorded faults and corrective actions performed.

Table 7. Summary of Faults and Corrective Actions, Endurance Operation				
MODEL/ NOMEN/ USA#	**PM**	**TEST MILES**	**FAULT DESCRIPTION**	**CORRECTIVE ACTION**
CUCV M1028A2 NG1LUF	NO	8376	fuel pump leak CL-1	replaced fuel pump
CUCV M1028A2 NG1KX2	NO	3288	engine idle low	adjusted idle speed
		7353	fuel pump leak CL-2	replaced fuel pump
CUCV M1028A2 NG1KHH	NO	Not Recorded	None	no corrective measures required
HMMWV M1037 NG2BL1	YES	1595	None	PM: replace fuel filter No corrective measures required
HMMWV M1037 NG2BL3	NOT STATED	708	CL-3 leak fuel-water sep	replaced petcock
		800	stall upon stop	adjusted idle speed
		800	CL-3 leak fuel hose leak	replaced fuel line
		1365	engine running rough	changed fuel filter
		2482	stall upon stop 2nd time	changed fuel filter 2nd
				adjusted idle speed
HMMWV M1037 NG2BL0	YES	1256	None	PM: replace fuel filter No corrective measures required
HMMWV M1037 NG2R3A	NOT STATED	163	stall upon stop	changed fuel filter
				adjusted idle speed
				cleaned fuel tank vent hose
		266	engine running rough	replaced fuel hose
		652	engine running rough	replaced fuel filter 2nd
				cleaned fuel tank vent hose
			CL-2 fuel hose leak	replaced hose clamp
		2685	fluctuating idle speed	adjusted idle speed
		4952	CL-2 fuel hose leak	repaired fuel hose
		5491	engine stalling	replaced #3 fuel injector
				replaced fuel water separator filter
HMMWV M1037 NG2R35	NOT STATED	28	failed fuel pump	replaced fuel pump

5-T TRUCK M923A2 NLOZK4	YES	508	None	PM: replace fuel filter
		125	engine idle low	adjusted idle speed
		656	CL-1 fuel hose leak	adjusted fuel hose clamp
5-T TRUCK M923A2 NLOZK7	YES	303	None	PM: replace fuel filter
		126	engine idle low	adjusted idle speed
5-T TRUCK M923A2 NLOZL3	NOT STATED	103	hard to start	adjusted fuel hose clamp
		126	engine idle low	adjusted idle speed
		319	hard to start	replaced fuel filter
				replaced fuel water separator filter
HEMTT M985 NPOEA4	NO	142	engine idle low	adjusted idle speed
HEMTT M985 NPO6DB	YES	453	None	PM: replace fuel filter
		3292	engine idle low	adjusted idle speed
HEMTT M985 NPO6D8	YES	690	None	PM: replace fuel filter No corrective measures required

Source: U.S. Army, *Biodiesel Fuel Evaluation for the U.S. Army Tactical Wheeled Vehicles* (U.S. Army TECOM 1994).

For the purpose of this thesis, the findings of the endurance operation sub-test are the most significant of any sub-test TECOM performed, due to the low incidence of engine or fuel system malfunction. Although there was no maintenance data of vehicle operations on JP-8 for direct comparison, the frequency and type of faults experienced during the sub-test did not strike TECOM as extraordinary. In TECOM’s summary report, they stated “the maintenance problems encountered should not be directly attributed to the biodiesel blend” (TECOM 1994, 41). The TECOM summary report further explained the probability of similar fuel-related problems being observed had JP-8 been introduced to the vehicle fuel systems, displacing DF-2, as occurred following Desert Storm in 1991. These findings and comments point to the conclusion that biodiesel-blended fuel causes no greater incidence of faults involving fuel delivery systems and engine operation--a significant finding of this thesis, directly answering one research question.

ASG Biodiesel Survey

Attitude Factors

ASG Renaissance (ASG) conducted the *Biodiesel End User Survey* from 2003 to 2004. The purpose of the survey was to obtain information from diesel fleet managers regarding fuel preferences. It quantified responses regarding use of biodiesel and interest in the use of biodiesel among vehicle fleet operators. The survey also quantified characterizations of satisfaction among vehicle fleet operators who use biodiesel or biodiesel-blended fuel, and measured their propensity to recommend its use to other fleet operators. The following paragraphs describe ASG's conclusions based on the survey, and relevance to this thesis in terms of biodiesel storage and dispensing, and performance factors.

Use of Biodiesel

Forty-five percent of fleets surveyed use biodiesel or biodiesel-blended fuel. B20 (20 percent biodiesel) is the preferred blend among survey respondents, accounting for 71 percent of users. Four percent use B60, and 13 percent use B100. The survey summary indicated that 16 percent use B5 or a lower-percentage blend, noting that some respondents are multiple-blend users.

This survey result is relevant for two reasons. It demonstrates that biodiesel is widely used among diesel vehicle fleets, in both private and public sectors. This indicates that biodiesel is not simply a “niche market” fuel. Second, this finding demonstrates that biodiesel is flexible, and can be used in various percentage blends. This flexibility is important because a plan to implement biodiesel-blended fuel among CONUS-based

U.S. Army tactical vehicles may be feasible even with a low-percentage blend.

Satisfaction of Biodiesel Users

All survey participants who use biodiesel or biodiesel blended fuel characterized their experience as favorable. Greater than half (54 percent) indicated having used biodiesel for two or more years. Sixty-seven percent of all biodiesel users surveyed described their experience as “trouble free,” and less than one-third (29 percent) claimed “minor problems.” Four percent of biodiesel users specified experiencing fuel quality problems.

This survey result pertains to this thesis in several different ways. It indicates 100 percent satisfaction among users of biodiesel. That is a testament to the performance characteristics of the fuel, and also to the quality of biodiesel produced and distributed commercially in the United States. The fact that more than half of the respondents have used biodiesel for two years or greater is consistent with evidence of satisfaction among long-term biodiesel users revealed in the literature review.

Interest in Using Biodiesel

Ninety-one percent of survey respondents indicated having a positive attitude concerning biodiesel. This figure includes the 45 percent using biodiesel and 46 percent of others not using biodiesel. Two recurring statements from participants' unsolicited comments account for this figure. Those statements were:

1. The desire to be perceived as environmental leaders.
2. The desire to receive Energy Policy Act (EPACT) new-vehicle purchase credits.

Fifty-one percent of survey respondents said Original Equipment Manufacturer (OEM) support for biodiesel would "definitely" be a consideration in future vehicle purchase decisions. This figure did not distinguish between biodiesel users and non-users.

Nine percent of fleet managers surveyed indicated a negative attitude concerning biodiesel. None of these respondents were biodiesel users. Objections cited were fuel cost, lack of available retail fueling stations, and inability to control or reduce NOx (nitrous oxide) emissions. Figure 3 shows biodiesel attitudes among survey participants, depicted as a percentage of survey respondents.

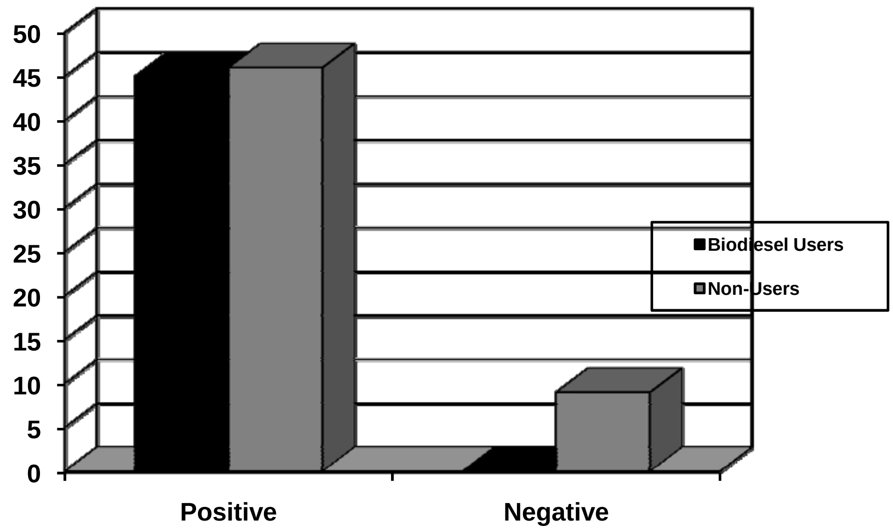

Figure 3. Attitudes Toward Biodiesel
Source: *Biodiesel End User Survey* (ASG Renaissance 2004).

This survey finding is important because it indicates a high level of interest in biodiesel among diesel fleet operators. It identifies the reasons for great interest, yet simultaneously identifies prohibitive factors to adopting biodiesel. Prohibitive factors such as cost and retail point-of-sale availability, though specified by fewer than 10 percent of all respondents, are more frequently cited in the literature review for why biodiesel has not displaced more petroleum diesel in the transportation fuel market.

Propensity to Recommend Biodiesel

When asked whether they would recommend biodiesel fuel to other vehicle fleet managers, 96 percent of survey participants who use biodiesel or biodiesel blended fuel responded affirmative. The four percent which responded negative indicated fuel cost as the primary factor, not performance, quality, availability, or any other specific factor.

Synthesis of the Two Studies

The TECOM study, *Biodiesel Fuel Evaluation for the U.S. Army Tactical Wheeled Vehicles*, is important because it is the sole source of biodiesel experimentation with U.S. Army tactical vehicles identified in open-source literature. Despite its age, approaching 14 years, this study contains insightful data regarding vehicle performance and vehicle fuel system problems when using biodiesel-blended fuel.

The ASG *Biodiesel End-User Survey* is important because it was the largest user survey identified in terms of the number of diesel-powered vehicles represented. The *Biodiesel End-User Survey* encompasses a wide range of fleets, representing public and private commercial sectors, as well as multiple vehicle manufacturer brands. Vehicle manufacturer data is pertinent to this thesis because U.S. Army tactical vehicles are powered by diesel engines from multiple manufacturers, such as Detroit Diesel, Caterpillar, and Cummins. The findings of high user satisfaction across the wide range of diesel vehicles in surveyed fleets translate to a high probability of satisfactory performance among U.S. Army tactical vehicles.

Vehicle performance data between the two studies is well correlated. In *Biodiesel End-User Survey*, 96 percent of respondents indicated problem free or minor problems regarding vehicle operation. Seventy-seven percent of tactical vehicles in the TECOM experiment exhibited only one fault per vehicle requiring corrective action. That percentage is even greater if the high-mileage vehicle models (HMMWVs) are excluded. Excluding HMMWVs, TECOM’s remaining test vehicles averaged 1.2 faults per vehicle throughout the 1-year duration of the endurance operation sub-test.

Specific to tactical vehicles, the *Biodiesel Fuel Evaluation for the U.S. Army Tactical Wheeled Vehicles* established parity between JP-8 and biodiesel blended fuel in two significant engine performance factors. Performance in terms of acceleration and towing capability was found to be virtually equal. Blended fuel parity is consistent with evidence in the literature review and corresponds to the high degree of user satisfaction described in *Biodiesel End-User Survey*. One representative unsolicited comment said “put it in the tank and go” (ASG Renaissance, 3). Within all attitudinal measures of the ASG survey, none responding negatively cited performance as their rationale.

The two studies also exhibit correlation in regards to fuel storage and distribution. TECOM stated that *Biodiesel Fuel Evaluation for the U.S. Army Tactical Wheeled Vehicles* required no change to their fuel storage and distribution procedures. In *Biodiesel End-User Survey*, 71 percent of respondents who use biodiesel indicated they made no modifications to fuel storage and maintenance procedures. Of other respondents that did modify storage and maintenance procedures, “storage tank cleaning (and) more frequent fuel filter changes” was cited (ASG Renaissance, 3). The survey fails to distinguish between bulk fuel storage and (vehicle) maintenance. However, in either case, the number of respondents represents a minority of biodiesel users and supports the conclusion that replacement or modification of storage containers is not required.

Quantity Gap Analysis

Table 8 contains information obtained from the Defense Energy Support Center (DESC) indicating sales of JP-8 to the U.S. Army in CONUS.

Table 8. U.S. Army (CONUS) JP-8 Sales by Fiscal Year			
Year	**FY 2005**	**FY 2006**	**FY 2007**
JP-8 Gallons	**77,375,789**	**72,993,538**	**78,364,574**

Source: Defense Energy Support Center (DESC), 2009.

For the purpose of this thesis, DESC sales of JP-8 to the U.S. Army in CONUS are assumed to be equal to the quantity consumed in tactical vehicles for the given fiscal year. Definitive consumption data could not otherwise be determined during the period of this research. Using the methodology described in chapter three, the following table shows the annual fuel requirement and estimated biodiesel quantity necessary to implement a B20 (20 percent biodiesel-blend) in the three defined CONUS regions.

<table>
<tr><th colspan="8">Table 9. Quantity Analysis to Determine Biodiesel Requirement in CONUS</th></tr>
<tr><th></th><th>Total Number of BCTs</th><th>Number of BCTs by Region</th><th>Total AVG Annual JP-8 Requirement (gallons)</th><th>AVG Annual JP-8 Requirement by Region (gallons)</th><th>Optimal Biodiesel Factor</th><th>Optimal Biodiesel Requirement by Region (gallons)</th><th>Total Biodiesel Requirement (gallons)</th></tr>
<tr><td>CONUS Region NORTH</td><td rowspan="3">63</td><td>14</td><td rowspan="3">76,245,000</td><td>16,943,333</td><td rowspan="3">20%</td><td>3,388,667</td><td rowspan="3">18,249,000</td></tr>
<tr><td>CONUS Region CENTRAL</td><td>25</td><td>30,255,952</td><td>6,051,190</td></tr>
<tr><td>CONUS Region SOUTH</td><td>24</td><td>29,045,714</td><td>5,809,143</td></tr>
</table>

Source: Created by author

According to the criteria established in the research methodology, the CONUS U.S. Army annual JP-8 requirement is a significant finding (biodiesel production is equal to or greater than 20 percent of the U.S. Army JP-8 requirement in any of the three defined geographic regions, and estimated biodiesel production capacity is greater than or equal to 20 percent of the total annual U.S. Army JP-8 requirement).

The research expected the U.S. Army's CONUS JP-8 requirement to be considerably greater. This thesis presumed that biodiesel production would be sufficient to only implement an optimal (20 percent) biodiesel blend in one, at best, of the three geographic regions. Surprisingly, the average annual JP-8 requirement, roughly 76 million gallons, is actually less than the 2007 national biodiesel production (490 million gallons), and merely four percent of the estimated 2007 national biodiesel production capacity (2.2 billion gallons).

Comparing the annual U.S. Army CONUS JP-8 requirement by separate geographic regions, the North has the lowest demand, approximately 17 million gallons, which is slightly greater than half of either the Central or South regions. The Central and South regions are nearly equal, each with demand of approximately 30 million gallons annually. To determine the quantity of biodiesel necessary to implement a blended fuel program, multiply these region totals by the percentage of biodiesel to achieve the optimal blend. In chapter three, this research established 20 percent as the optimal blend. The resulting total biodiesel necessary is approximately 18 million gallons. This figure equates to about four-percent of the biodiesel produced nationally in 2007, and less than one-percent of the biodiesel production capacity estimated for that year.

Summary

Chapter 4 presents the analysis of the U.S. Army TECOM *Biodiesel Fuel Evaluation for the U.S. Army Tactical Wheeled Vehicles* experiment and the ASG *Biodiesel End-User Survey*. Analysis of these separate source findings and synthesis of these case studies answers the first two research questions:

1. Does biodiesel-blended fuel cause any greater incidence of engine malfunction than standard diesel fuel (JP-8) in U.S. Army tactical vehicles?

2. Does biodiesel-blended fuel require modification to the U.S. Army's existing fuel storage and distribution infrastructure?

According to TECOM, biodiesel-blended fuel caused no increase to incidents of fuel system fault or engine malfunction. Specifically, TECOM researchers said "the maintenance problems encountered should not be directly attributed to the biodiesel blend" (TECOM 1994, 41). This finding is supported by evidence in the ASG survey, where 96 percent of respondents who use biodiesel indicated a high degree of satisfaction in their experience.

With respect to fuel storage, both sources suggest that no modification to the U.S. Army's fuel infrastructure is required to use biodiesel-blended fuel. TECOM stored pure biodiesel and biodiesel-blended fuel in existing U.S. Army fuel containers for the duration of their one-year experiment. Additional containers were used to store biodiesel-blended fuel, and to dispense periodically to test vehicles. A high percentage of respondents in the ASG survey indicated no fuel storage modifications, though a small number did report more frequent storage tank cleaning as a change to their bulk fuel storage practices.

Quantity gap analysis answered the third research question:

3. What quantity of biodiesel is required to displace a portion of the U.S. Army's (CONUS) annual fuel (JP-8) requirement?

Results of the quantity analysis were the most significant finding of this study, because the figures were unexpectedly low. The U.S. Army CONUS JP-8 requirement is approximately 76 million gallons annually. The amount of biodiesel necessary to displace 20 percent of the U.S. Army's JP-8 requirement in CONUS is 18 million gallons, or merely 15 percent of the biodiesel produced in the U.S. in 2007. From a quantitative perspective, this study concludes it is feasible to displace 20 percent of the U.S. Army's CONUS JP-8 requirement with biodiesel.

While the research did not raise any new issues, this study found the use of these particular cases lacking in some respects. Regarding the ASG *Biodiesel End-User Survey*, two limitations are worthy of mention. First, the ASG survey addressed the issue of fuel storage as a companion issue to vehicle maintenance. The survey report did not distinguish between fuel storage practices and vehicle maintenance practices. As a result, it is not clear whether survey respondents experienced fuel storage problems, vehicle maintenance problems, or both. Second, the ASG survey grouped all respondents who identified themselves as biodiesel users, regardless of the percentage blend of fuel they used (2 percent to 100 percent). Specificity based upon users of fuel with varying percentage blends would afford insight to the research questions regarding vehicle performance and fuel storage.

Within TECOM's *Biodiesel Fuel Evaluation for the U.S. Army Tactical Wheeled Vehicles*, this study identified one issue where that source could have been more complete. The TECOM study provided an excellent summary of vehicle faults and maintenance performed throughout the test. However, this research would have benefited from comparison data for like-vehicle types during the same period.

The case findings and the quantity analysis results described in this chapter form the basis of conclusions and recommendations presented in chapter 5.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Introduction

In the present era of constrained energy resources and a globally burgeoning energy demand, America's energy security is synonymous with national security. The United States requires a domestically produced and sustainable energy source to fuel its Army.

Biodiesel is an Environmental Protection Agency (EPA) registered and approved alternative fuel which meets these requirements. Volumes of research and analysis support the use of biodiesel or biodiesel-blended fuels across a broad spectrum of applications. Little research, however, is specific to U.S. Army tactical vehicles. The purpose of this thesis, therefore, is to determine whether biodiesel is a feasible fuel for U.S. Army tactical vehicles. This thesis seeks to answer the following research questions:

1. Does biodiesel-blended fuel cause any greater incidence of engine malfunction than standard diesel fuel (JP-8) in U.S. Army tactical vehicles?

2. Does biodiesel-blended fuel require modification to the U.S. Army's existing fuel storage and distribution infrastructure?

3. What quantity of biodiesel is required to displace a portion of the U.S. Army's CONUS annual fuel (JP-8) requirement?

Chapter 4 presented findings from two biodiesel research studies consisting of quantitative and qualitative data. This thesis synthesized those findings and examined their relevance to the research questions listed above. This thesis also performed a quantity gap analysis to compare U.S. Army CONUS JP-8 fuel requirements and national biodiesel production. Together, these analyses are the basis of this study's conclusions and recommendations for additional study or research.

Conclusions

The findings of the two studies are consistent with the wider body of research found in the literature review for this thesis. *Biodiesel Fuel Evaluation for the U.S. Army Tactical Wheeled Vehicles* demonstrates that factors or measures of diesel engine performance generally improve when using biodiesel-blended fuel. The specific factors measured by TECOM were vehicle acceleration, towing capability, and engine exhaust smoke opacity. Endurance operations indicated neither an increase nor decrease in engine performance, as measured by frequency of corrective maintenance over the one year test period. Attitudinal factors, measured by ASG, demonstrate that biodiesel use is viewed positively among diesel vehicle fleet operators, by both those who do and those who do not use biodiesel. Among diesel vehicle fleet operators who do not use biodiesel, strong interest in the fuel exists. Of survey respondents who do use biodiesel, ninety-six percent indicated they would recommend biodiesel to other fleet operators.

The first research question is affirmed by the findings of the two studies. In *Biodiesel Fuel Evaluation for the U.S. Army Tactical Wheeled Vehicles*, TECOM operated fourteen tactical vehicles extensively on biodiesel-blended fuel with no engine malfunctions attributed to the fuel. Where vehicle fuel system faults did occur, such as leaks, TECOM attributed those faults to the solvent characteristic of the fuel. This result is consistent with other observations revealed during the literature review. One explanation is that until 1994, many automotive manufacturers used nitrile rubber or natural rubber components in fuel system hoses, gaskets, and seals. Since that time, more impervious synthetic materials are used. In the *Biodiesel End-User Survey*, over half (54 percent) of the respondents who claimed to use biodiesel had greater than two years experience using the fuel. An even larger percentage (96 percent) of respondents who use biodiesel characterized their experience as “trouble-free” or “minor problems.”

The second research question is also affirmed in the synthesis of the two studies. In *Biodiesel Fuel Evaluation for the U.S. Army Tactical Wheeled Vehicles*, TECOM stated that no modifications were made to their fuel storage and dispensing procedures. Pure biodiesel was stored in existing fuel containers. It was blended with JP-8 periodically in 500-gallon tanks, and dispensed into test vehicles as necessary. TECOM employed this procedure throughout the one-year test period. TECOM’s summary report made no mention of fuel storage and dispensing issues. ASG’s *Biodiesel End-User Survey* provided slightly more detail regarding this specific question. According to respondents who used biodiesel, 71 percent made no modifications to their fuel storage or maintenance procedures. The only further definition provided in the report summary indicated that “storage tank cleaning (and) more frequent fuel filter changes were the most frequently mentioned changes to routine” (ASG Renaissance 2004, 3). The report’s imprecise writing fails to distinguish between fuel storage and maintenance, but evidence in the literature review supports the affirmative conclusion. When switching to biodiesel or blended fuel, very few operators must make physical modification to fuel storage containers. Some biodiesel users implement more frequent fuel tank cleaning regimens. Some biodiesel users also alter their vehicle maintenance schedules to include more frequent fuel filter changes.

The third research question is undoubtedly the most significant finding of this study. Author Greg Pahl indicated in his book, *Biodiesel: Growing A New Energy Economy*, that the total quantity of petroleum diesel consumed annually in the U.S. is about 35 billion gallons, and that this figure dwarfs the quantity of biodiesel produced annually in the United States (Pahl 2005, 167). Further literature revealed facts noted in preceding chapters of this study. First, that the U.S. Department of Defense is the largest consumer of petroleum in the United States (Bender 2007) and second, that the U.S. Army consumes about 50 million gallons of JP-8 on a monthly basis in Iraq and Afghanistan (Flaherty 2008). Initially, given these types of figures, the author assumed that the U.S. Army's CONUS annual JP-8 requirement would likewise dwarf national biodiesel production. Such is not the case, however. This study reveals, by data obtained in open-source research and through a Freedom of Information Act request, that current biodiesel production is sufficient to displace 20 percent of the U.S. Army's total JP-8 requirement within CONUS.

Recommendations

The research indicates that biodiesel possesses very good performance characteristics, generally, and in U.S. Army tactical vehicles, specifically. Yet, the data represents a small sample of U.S. Army tactical vehicles in an experiment conducted nearly 15 years ago. This thesis recommends additional research and experimentation among a larger sample of tactical vehicles, including tracked vehicles and other wheeled vehicles not included in TECOM's experiment. Additional research and experimentation would yield a larger sample of data, plus specific data regarding performance factors and maintenance requirements in U.S. Army tactical vehicles. Findings of broader experimentation, if consistent with TECOM's *Biodiesel Fuel Evaluation for the U.S. Army Tactical Wheeled Vehicles*, may enable biodiesel to be implemented within CONUS.

This thesis excluded fuel cost as a factor in determining whether it is feasible to fuel U.S. Army tactical vehicles in CONUS with biodiesel. But fuel cost may become a significant consideration in the near future, especially if the fuel price spike in the summer of 2008 is an indicator. Therefore, another recommendation for additional research is cost analysis to determine at what point biodiesel becomes advantageous to displace a percentage of the U.S. Army's CONUS JP-8 requirement.

This thesis found extensive evidence beyond *Biodiesel End-User Survey* that biodiesel users are positive about their experience. A third recommendation for further research is to conduct a survey similar to *Biodiesel End-User Survey* among Government Services Administration (GSA) fleets within the Department of Defense. Many GSA fleets currently use biodiesel blends (B20) in their diesel-powered administrative and installation support vehicles. Some have done so since 2000, in order to meet Energy Policy Act alternative fuel mandates (National Biodiesel Board 2003). There is anecdotal evidence of user satisfaction among these GSA fleets in the literature review, but the author found no indications of quantitative results. A research effort similar to *Biodiesel End-User Survey* would provide quantifiable measures of satisfaction among GSA biodiesel users.

Finally, the Army should continue to investigate alternative fuels and energy sources for tactical vehicle applications. Alternative energy solutions are critical in light of the eventual decline of global petroleum resources, and the obvious trend of increased competition for those resources. Experts suggest that no single alternative fuel, like biodiesel, is capable of fully displacing petroleum diesel. Rather, they advocate the idea that an overall solution to petroleum dependence lies in a multi-source approach, including electric, biofuels, and biofuel-electric hybrids, among other sources.

GLOSSARY

alkyl-ester. A generic term for an organic compound formed when vegetable oil, an acid, and an alcohol are mixed. The term applies to both methyl-esters and ethyl-esters, depending upon which alcohol (methyl alcohol or ethyl alcohol) is used. Alkyl-ester is another name for biodiesel.

Alternative fuel. A fuel derived from renewable sources as a substitute to fossil fuels.

Biodiesel. An alternative fuel produced from vegetable oils or animal fats through a process called transesterification.

Biodiesel-blended fuel. Petroleum diesel mixed with biodiesel, expressed as a percentage of volume. For example, a volume containing five-percent biodiesel is B5, a volume containing twenty percent biodiesel is B20, et cetera.

Biofuel. Energy-crop-derived liquid fuels such as biodiesel, ethanol, and methanol.

Carbon dioxide. An odorless, colorless, non-poisonous gas which is the waste product of cell respiration and the combustion of fossil fuels.

Carbon monoxide. An odorless, colorless, poisonous gas which is the product of incomplete combustion of carbon (i.e. burning fossil fuels).

Cetane. The combustion or ignition quality of diesel fuel, indicated with a scaled-number system called cetane number.

Cloud point. The temperature at which wax-like solids first appear in diesel fuel.

Cladosporium resinae. A bacteria which can develop in diesel fuel.

Cold filter plug point. The temperature at which semi-solid diesel fuel no longer flows through a fuel filter element. Cold filter plug point is lower than cloud point, but higher than pour point.

DF-2. Commercial grade diesel fuel sold in the United States for on-road vehicles.

Energy Efficiency Ratio. A numerical figure representing the energy stored in a fuel compared to the total energy required to produce, manufacture, transport, and distribute the fuel.

Ethanol. A volatile, clear alcohol derived from sugars and starches from crops. Also called ethyl alcohol.

Fossil fuel. A non-renewable fuel or energy source which was formed naturally over time from the remnants of prehistoric organic material.

Feedstock. A substance converted to another form of fuel or energy.

Flash point. The temperature at which a substance will ignite.

Glycerin. A substance which is part of the chemical make up of vegetable oils, separated during the process of transesterification. A byproduct of biodiesel production.

Humectant. A substance which captures and retains moisture, used to reduce dust on gravel roads, dirt tracks, and arenas.

JP-8. A kerosene-type turbine fuel produced to meet military aircraft/vehicle system specifications (contains special formulation additives).

Lubricity. A measure of capacity to reduce friction of solid surfaces in relative motion.

Methanol. A volatile, clear alcohol derived from wood used as a solvent or race-car fuel. Also called methyl alcohol.

Methyl-esters. Biodiesel that is made with methanol or methyl alcohol.

Nitrogen oxides. A product of combustion and a contributing factor in the formation of smog or visible pollutants suspended in the atmosphere.

Opacity. The measure or degree of transparency of a substance.

Operational profile. The conditions or physical environment which may be expected during performance of a mission or series of missions.

Particulate matter. Small combustion residue that is discharged in an engine exhaust.

Petroleum. Fuel derived from refined crude oil.

Pour point. The temperature at which a liquid fuel becomes solid, and will not pour.

Pseudomonas aeruginosa. A bacteria which can develop in diesel fuel.

Petrodiesel. Diesel fuel produced by refining crude oil.

Snap-idle. The act of fully depressing a vehicle’s accelerator pedal for 1-2 seconds, and then releasing the pedal to resume idle speed.

Solvency. A measure of capacity to act as a detergent or cleanser.

Total hydrocarbons. Organic compounds consisting entirely of hydrogen and carbon (such as benzene or methane) present in petroleum products and natural gas.

Transesterification. A chemical process using an alcohol to react with triglycerides in vegetable oils or animal fats to produce biodiesel and glycerin.

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